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INEQUALITIES OF SEDIMENTATION[1]

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INTRODUCTION

Most of the earlier discussions touching the subject of sedimentation leave in the mind of the reader the impression that water-laid sediments other than delta deposits accumulate over very wide areas at a nearly uniform rate. Leaving out of consideration delta and estuarine sediments whose relatively rapid accumulation is of course universally recognized, variability or contrast in rates of deposit between different areas and between different periods in the same area rather than uniformity appears to the writer to be the dominant feature characterizing sedimentation. In both its time and space relations sedimentation is highly variable.

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[1] Published with the permission of the director of the Geological Survey of Canada.

It is the purpose of the present paper to point out some of the factors which make for periodic variability in the rate of deposition and to cite some examples from existing lakes and seas to illustrate the sharp contrasts in the rate at which sediments accumulate at different points near the same coast line.

Some familiarity with the mobility of wind-formed deposits is unavoidable, but with the far greater mobility of water-laid deposits we have a comparatively slight acquaintance. We are apt to think of clastic deposits which have once come to rest on sea or lake bottom as permanently fixed. That such materials lose nearly half their weight in water and in a corresponding degree their tendency to "stay put" is apt to be forgotten in considering the history of geological formations. Removal or migration of parts or the whole of an unconsolidated formation may occur much more rapidly below than above sea level. The buoyancy of water, together with the general absence of the fixing influence of vegetation, gives to unconsolidated aqueous deposits under the combined influence of waves and currents a far greater degree of mobility and instability than subaërial deposits possess.

CLASTIC DEPOSITS

Observations on the Great Lakes.—Previous to human interference sand dunes represent in a moist climate an established equilibrium between the forces of the winds and the waves and the stabilizing influence of vegetation. The slightest interference by man with the vegetable covering of a sand hill country which is usually found in temperate climates may, however, start the dunes of a whole region traveling. It is said that the highest dune of Friesland owes its origin to the destruction of a single oak. Water-laid deposits represent a similar balance of forces in which water currents replace air currents.

The deposits of the foreshore represent the innermost zone of sedimentation. They may be examined in part at least from the vantage ground of the shore. Because of their comparative accessibility to observation the deposits of bars, tickles, and spits illustrate well the irregular and highly localized character of the inshore deposits.

The shores of the Great Lakes afford examples of these massed aggregations of sand and gravel flanked by extended areas of shoreline along which little or no deposition of sediment occurs. The south shore of Lake Erie east of Sandusky is nearly everywhere composed of Devonian shales or glacial till, the wave and current action being destructive instead of constructive. At Erie, Pennsylvania, however accretion dominates the elsewhere prevailing erosion and a long, broad spit has been built into the lake inclosing Erie harbor.

On the Canadian shore of Lake Ontario at Toronto, in sharp contrast with the bare rock bottom frequently found near the shore of Prince Edward county, there is a sand spit building out into water nearly 200 feet deep. In the Burlington bar which extends from the north to the south shore of Lake Ontario five miles from the western end of the lake we have in the maximum depth of the enclosed lagoon, 80 feet, an approximate measure of the total thickness of the bar deposit which has been built up during the relatively short life of this lake. Convincing evidence that bars form even far more rapidly than such a figure would suggest is furnished by the observations of Russell[1] on a bar at Round Island in Lake Huron. Two photographs by Russell taken ten years apart show that the bar increased 1000 feet in length during this interval. Observation of the movement of littoral drift along the shore of Lake Ontario affords equally clear evidence of the rapid movement of very coarse sediments and shingle. In the vicinity of Oakville the littoral drift is westward. Two piers built out into the lake at this point on opposite sides of a river mouth to protect navigation act as groins. Nothing accumulates on the beach behind the west pier, thus showing that there is no movement of material toward the east. Alongside the east pier, however, the beach is growing out into the lake and during periods of rough weather the westerly moving shingle nearly overwhelms the base of the pier and the building near it.

In the Great Lakes the vigorous action of currents is by no means confined to the immediate vicinity of the shoreline. A curious feature of their behavior is its capricious character, reminding one of fitful gusts of wind on a stormy day. A single excerpt from the notes of Mr. E. J. Whittaker on the behavior of currents in Lake Erie 2 miles south of Point Pelee will illustrate this.

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[1] Russell, "A Geological Reconnaissance along the North Shore of Lakes Huron and Michigan," *Geol. Surv. of Michigan* (1905), p. 104, Pl. 15.

> Water depth 18–20 feet; float at depth of 15 feet; average current rate 1.91 miles per hour. Current here alternately slackened and quickened. Off this point I also got a good illustration of this with a small motorboat while soundings were being taken by Philp's men. The motorboat running at perhaps 2½–3 miles per hour for intervals of three minutes at a time was unable to make any headway at all. The current then suddenly slackening, the boat would fairly bound forward as though released from a chain. This was the most notable instance of a strong varying current. Moreover here the current changed its direction completely inside of 45 minutes, first being a strong easterly current and at the conclusion of observation being from the west.

In direction the lake currents are variable but only within certain well defined limits. At Southwest Shoal light-ship, a short distance from the station referred to above, current observations which continued over a period of two months during the summer of 1918 showed easterly and westerly currents with about equal frequency but no other direction is represented. Another Lake Erie station which was occupied for some weeks shows only southerly currents. It is therefore certain that the work accomplished by lake currents is not of a haphazard character and that some of their general results in sedimentation can be inferred with certainty when a sufficient amount of data on their behavior becomes available.

Littoral marine deposits.—The movement of sediments along the shores and over the bottoms of the Great Lakes, although it is considerable, is far outclassed in volume by the material which is constantly passing over the littoral zone of many sea coasts. The construction of harbor defenses against the sea sometimes affords surprising evidence concerning the volume of sediments which moves along the sea bottom in front of the foreshore. Instructive evidence concerning the great volume of such traveling sediments on some parts of the sea shore is furnished by the history of the Madras Harbor in India.

> The Indian Government in 1876 determined to construct an enclosed harbour at Madras. Careful observations were made of the volume of sand travel, and it was estimated that it would take 180 years for the travelling

sand to fill a triangular area between the coast line and a breakwater running out 1,200 yards from the shore. No sooner, however, were the works commenced than it became obvious that the above estimate of sand travel was completely unreliable. The wave-borne sand travelling up from the south was about sixty times greater in volume than the corresponding amount brought down by the northeast monsoons. The original estimate of sand in motion was 243,000 tons per annum; a second estimate in 1904 was 550,000 tons per annum. The accumulation at the present time shows that about 1,000,000 tons per annum travel along the coast line. Low-water line between 1876 and 1912 has crept seawards for a distance of 2,500 feet. In 1881 a terrific cyclone wrecked the harbour works then nearly completed but a somewhat similarly outlined harbour has since been carried out on altered lines. For a distance of more than 3 miles severe erosion has taken place on the north side of the harbour due to the arrest of the normal volume of travelling sand, and whole towns and villages have thus been swept away. This experience is an extreme instance of the action which goes on in a greater or less degree at every headland, river-mouth or solid projection from a foreshore into the sea.[1]

It may be noted here that the migration of clastic materials in the littoral zone is not confined to the finer products of erosion but comprises much coarse material and even heavy blocks of stone.

Rollers bring in shingle and sometimes large masses of rock from deep water. It frequently happens that, after a severe gale in the channel, boulders weighing several hundredweight will be found strewn along the strand. These are mostly weed-covered. The growth of weed evidences the fact that the action of the waves has reached sea depths normally tranquil. In exposed portions of the coast line of Scotland boulders upwards of 2 tons in weight are similarly thrown up after storms and their occurrence on these spots is so much a matter of course that they go by the name of "travellers." Their buoyancy being increased by the crop of seaweed they carry, they are pushed along the sea bed under the impulsion of the deep-water rollers. As an instance of deep-sea wave action may be cited the fact that concrete blocks at Peterhead harbour weighing 47 tons were forced out of position at a depth of 40 feet below low water.[2]

The English Channel is an area over much of which clastic sediments pass without stopping to build up formations. The detailed explorations of the bottom of the English channel made by

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[1] A. E. Carey, "The Sanding up of Tidal Harbours," *Proc. Inst. C.E.*, CLVI (1903–4), 1–90; A. E. Carey and F. W. Oliver, *Tidal Lands*. Blackie & Sons, Ltd., (1918), pp. 144–45.

[2] *Op. cit.*, p. 150.

French engineers[1] many years ago in connection with the proposed submarine railway tunnel showed the sea floor to be free of unconsolidated or recent deposits from the French to the English coast between Dover and Calais. Because of the prevailing westerly and southwesterly winds the normal littoral drift in the English channel is eastward, so that most of the detrital material which passes through it doubtless comes to rest in the North Sea. Much of the coarse materials stop on the Dogger bank. This bank which is bounded by the 20-fathom line and covered by quartz sand is comparatively free from the finer silt which occurs in the deeper parts around it.[2] The sand and mud formations now forming in the North Sea represent the time interval since the submergence of the North Sea and English Channel area. These deposits probably thin out gradually toward the Channel where this considerable time interval is entirely unrepresented by any sediments. This it will be noted gives a relationship of areas where a formation is absent, relatively thin, and comparatively thick, which when met with in the consolidated rocks is generally ascribed to overlap. The Potsdam sandstone of New York and Ontario affords a comparable example. It is absent in the upper Ottawa valley, less than 100 feet thick over much of the southeastern Ontario but reaches a thickness of several hundred feet in eastern New York. Its progressively decreasing thickness from Lake Champlain to Ottawa is generally ascribed to overlap.

In the enclosed Arctic seas west of Greenland McMillan reported currents with a usual velocity of about 2 miles an hour.[3] In the same region Low has made the important observation that

> With bodies of water having a general north-south trend the current will flow north on the east side and south on the west side while in east and west bodies the direction will be west on the north side and east on the south side.[4]

On the Greenland side a southerly current comparatively free of ice allows the open sea to raise the general temperature while on the Elsemere side the Arctic current with its continuous stream of ice blocks the bays and does not allow the open water to ameliorate the cold of the ice covered lands.

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[1] A. Strahan, "The English Channel," *Nature*, XXV (1882), 463-67; *Lond. Geog. Jour.*, XXXI, 420.

[2] *Royal Comm. on Coast Erosion and Afforestation*, III (1911), Part 1, p. 9.

[3] J. G. McMillan, *Report of the Cruise of the Dominion Government Steamer Arctic in Northern Waters, etc., in 1908-9*, p. 469.

[4] A. P. Low, *Cruise of the Neptune* (1906), p. 289. Canadian Government.

It is evident that currents trending in opposite directions on opposite sides of narrow sea ways will tend to develop marked contrasts in the kind as well as in the amount of sediments which they distribute in comparatively limited areas.

In Chesapeake bay Hunter has shown that both erosion and accretion are contemporaneously in progress in adjacent parts of the bay. He finds that in the area studied, "The areas subjected to erosion aggregate 35 square miles and those subjected to sedimentation 9 square miles, making an excess of 26 square miles eroded."[1]

In the Bay of Fundy the processes of deposition and scour are both active as Matthew[2] has pointed out. His statement is summarized as follows:

> In the Bay of Fundy the velocity of the tide varies from two to three knots at its mouth to seven or eight knots in the Parrsboro passage near its head. Near its mouth, on the New Brunswick side, a portion of the bay is separated by a chain of islands, and is called Passamaquoddy Bay. . . . . The rush of the tide through these passes causes a roaring sound which may be heard for many miles, and the whirlpools in them are strong enough to upset boats and careen large vessels; both channels are full of deep holes, ledges, and pointed rocks. At Quoddy River the tide passes over barriers having only fifteen fathoms of water at low tide, yet within owing to the erosion of the tidal currents, there is fifty fathoms in the narrowest and straightest part, and thirty fathoms where it merges into the shallower water of Passamaquoddy Bay. . . . . Up in Chignecto Passage also off Cape Enrage, there is a trough scooped. out by the tide, which is outlined by the thirty, twenty-five, and twenty-fathom contour lines. . . . . But it is in the eastern arm of the Bay of Fundy—Minas Channel and Basin—that the scouring action of the tide is most conspicuous. . . . . The violence of the current in the deep troughs of Minas Channel and Basin occasions the roughest bottom observable anywhere in the bay, for at these points rock and gravel compose the bottom over which the tidal waters run. . . . . The north side of the Bay of Fundy having the slower run of tide, and being that along which the principal rivers enter, has in parts a muddy

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[1] J. F. Hunter, "Erosion and Sedimentation in Chesapeake Bay around the Mouth of Choptank River," *U. S. Geol. Surv. Prof. Paper 90B* (1914), p. 14.

[2] G. F. Mathew, "Report on the Superficial Geology of Southern New Brunswick," *Can. Geol. Surv. Rept. of Prog. for 1877–78* (1879), pp. 18EE–22EE.

> bottom. The only mud-bank of considerable volume is that formed by the sediment which the St. John River carried to the sea. It begins at the harbor of St. John and extends westward along the coast as far as the small islands called The Wolves, its outer limit coinciding nearly with the fifty fathom line. . . . . As a rule where the movement of the current exceeds one and a half knots mud is not deposited on the bottom of the bay.

Current work in deep water.—It must be pointed out that non-deposition and scour is not confined to shallow and narrow sea ways. Ocean currents are known to sweep the sea floor at considerable depths and at considerable distances from land. At the head of the Bay of Bengal the great delta deposits of the Ganges and Brahmaputra rivers are interrupted by a deep channel called the "Swatch of no ground" which is kept open presumably by some acceleration of the tidal currents. This channel which has a depth of 200 to 300 fathoms terminates abruptly on the west side in water only 5 to 10 fathoms deep.[1] Thus we have in the midst of an area in front of the mouths of the two greatest rivers of India where sedimentation proceeds with great rapidity a belt of sea bottom where deposition is supplanted by scour.

Off the west coast of Scotland tidal currents of great strength are known at some points to sweep the bottom at a depth of nearly 100 fathoms. Between Glas Island and Sgeir-i-Noe in the Little Minch off the west coast of Scotland the flood-stream often takes the buoys of the long lines down "and it is a remarkable circumstance, indicative of the great depth of the tidal-stream here, that the buoys though anchored in 70 or 80 fathoms are taken completely to the bottom; starfish and other marine animals being found attached to them."[2]

The laying of the transatlantic cables brought to light evidence of powerful currents at unexpected depths.

> Perhaps the most marked experience we have had of currents at great depths was in the case of the Falmouth cable near Giberaltar. At 500 fathoms the wire was ground like the edge of a razor and we had to abandon it and lay a cable well inshore. Captain Nares, of the surveying ship *Nemesis*, I

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[1] James Ferguson, *Quart. Jour. Geol. Soc.*, XIX (London, 1863).

[2] *Sailing Directions for the West Coast and Islands of Scotland from the Mull of Cantyre to Cape Wrath*, p. 119.

> think, with tangles could get no specimen of the bottom whatever, and he thinks he got sufficient evidence to prove the existence of a perfect swirl at that depth. . . . .[1]

South of the Azores, Hjort found considerable tidal currents down as deep as 800 metres.[2] Reade[3] has pointed out the evidence which certain relatively deep soundings afford regarding the irregularity of deposition. "In the Little Minch there is a 'deep' between the Isle of Skye and North Uist with a sounding of 107 fathoms, 'rock' the surrounding bottom with soundings from 50 to 90 fathoms being shells, sand, or mud."

Between the island of Rum and the island of Barra there are a good many soundings showing rock, which are deeper than others in the vicinity which have muddy bottoms.

> If we find hard ground we know that there must be something to prevent the accumulation of sediment. Now the only thing that prevents the accumulation of sediment is a current, and one help that telegraph soundings have thus given to geographical science as an indication that tidal currents exist even at very great depths in the open ocean.[4]

Most if not all deep-sea naturalists have noted even in the deeper parts of the continental shelf evidences of current action. Verrill has pointed out in the following quotation how such currents over certain areas southeast of New England have prevented the formation of argillaceous sediments.

> The prevalence of fine sand, along the Gulf-stream slope in this region, and the remarkable absence of actual mud or clay deposits indicate that there is here at the bottom, sufficient current to prevent for the most part the deposition of fine argillaceous sediments over the upper portion of the slope, in 65 to 150 fathoms. Such materials are probably carried along till they eventually sink into the greater depths nearer the base of the slope or beyond, in the ocean basin itself where the currents are less active. It is probable

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[1] Quoted by T. Mellard Reade, in "The North Atlantic as a Geological Basin," Presidential Address, Liverpool Geol. Soc. Session, 1885–86.

[2] Johan Hjort, "The Michael Sars North Atlantic Deep-Sea Expedition 1910," *Geog. Jour.*, XXXVII, 349–77.

[3] T. Mellard Reade, "Tidal Action as an Agent of Geological Change," *Philosophical Mag.*, XXV (1888), Series 5, p. 514.

[4] *Ibid.*, p. 514.

that such a movement of the water may be partly due to tidal currents, as well as to the actual northward flow of the Gulf Stream which is here slow, even at the surface.[1]

Charles Darwin long ago discussed some of the striking examples of inequalities in sedimentation which occur in the Red Sea and in the West Indies. The extent to which the significance of his very important observations appears to have been neglected by geologists may justify the following quotations from them.

> The area of deposition seems less intimately connected with the debouchment of the great rivers than with the course of the sea-currents; as is evident from the vast extension of the banks from the promontories of Yucutan and Mosquito. . . . .
>
> Besides the coast-banks there are many of various dimensions which stand quite isolated; these closely resemble each other; they lie from 2 or 3 to 20 or 30 fathoms under water and are composed of sand, sometimes firmly agglutinated with little or no coral; their surfaces are smooth and nearly level, shelving only to the amount of a few fathoms very gradually all round towards their edges, where they plunge abruptly into the unfathomable sea. This steep inclination of their sides which is likewise characteristic of the coast banks is very remarkable: I may give as an instance, the Misteriosa Bank on the edges of which the soundings change in 250 fathoms horizontal distance from 11 to 210 fathoms; off the northern point of the bank of Old Providence in 200 fathoms horizontal distance the change is from 10 to 152 fathoms; off the Great Bahama Bank in 160 fathoms horizontal distance the inclination is in many places from 10 fathoms to no bottom with 190 fathoms. On coasts in all parts of the world where sediment is accumulating something of this kind may be observed; the banks shelve very gently far out to sea and then terminate abruptly. . . . . I may observe, although the remark is here irrelevant that geologists should be cautious in concluding that all the outliers of any formation have once been connected together for we here see that deposits, doubtless of exactly the same nature, may be deposited with large valley-like spaces between them. . . . . [2]

> I may instance the great banks of sediment within the West Indian Archipelago, which terminate in submarine slopes, inclined at angles of between 30 and 40 degrees, and sometimes even at more than 40 degrees. . . . . That in some cases, the sea instead of spreading out sediment in a uniform sheet, heaps it round submarine rocks and islands it is hardly possible to doubt, after having examined the charts of the West Indies.[3]

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[1] Verrill, "Marine Faunas off New England Coast," *A.J.S.*, XXIV (1882), 449.

[2] Charles Darwin, *Geological Observations* (1851), Part I, pp. 196–97.

[3] *Ibid.*, Part II, pp. 133–37.

In the light of the abundant evidence it is hardly possible to doubt that currents play a great rôle in localizing the accumulation of sediments. In the words of the late Clement Reid:

> There is a general impression that marine action cannot go on much below low water; but this is altogether a mistake. Tidal scour may go on at any depth, provided the current is confined to a narrow channel, so as to obtain the requisite velocity. If in addition there is a to-and-fro motion such as that caused by the Atlantic swell at depths of at least 50 fathoms, the actual current required to remove even coarse sand need only be very gentle. The oscillation in one direction may not reach the critical velocity; in the other this velocity may just be exceeded; the movement, therefore, of the sand grains may always be in one direction especially if the courses taken by the ebb and flood tides do not coincide, or their velocities differ.[1]

The relative importance in sedimentation of the rôle of wave action which is constantly before our eyes is apt to be overestimated. Current action which even when most vigorous is seldom visibly in evidence is apt on the other hand to be unduly minimized.

Shifting of deposits.—The power of currents to transport sediments is nearly everywhere subject to periodic variations resulting from the influence of storms. In some regions there appears also to be a seasonal acceleration and retardation of tidal currents. Branner was told by a pilot on the Brazilian coast "That the currents inside of the Abrolhos and Parcel das Peredes reefs set strongest to the southwest in May, June, and July; that they run in the same direction at other times of the year, but not so strongly." Such variations in current velocity must result frequently in considerable deposits being laid down and subsequently removed by the same current.

A change in depth of wave base and in the courses of currents resulting from the elevation or depression of a coast line may result in shifting the position of an entire formation. As Vaughan Cornish[2] states, "A very small disturbance of conditions if long continued can shift the largest shoal. Such a disturbance is the recession of the coast line. It is probable that a shoal off the coasts of our eastern counties [England] tends to travel at the same rate as the coast is cut back."

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[1] Reid, *Submerged Forests* (New York: G. P. Putnam's Sons, 1913), p. 85.

[2] Cornish, "On Sea Beaches and Sand Banks," *Geog. Jour.*, XI (1898), 641.

Observation of surface currents alone will afford no positive evidence concerning the direction in which bottom formations are growing, nor their source. On the shoal east of Gorda bank the direction of the flow is nearly at right angles to the surface current. North of Barbados 60 miles Pilsbury[1] found at different levels between the surface and 200 fathoms, currents flowing in three different directions, simultaneously the lower at right angles to the surface.

Relative aridity.—The average annual loss by erosion is 95 tons for every square mile of the United States, excluding the Great Basin, according to an estimate published by the U.S. Geological Survey. The enormous volume of sediment which this contribution from nearly 3,000,000 square miles yields is distributed around the continental shelf of North America with a degree of irregularity corresponding to a number of variable factors. Among these factors are the variability in the rate of rainfall, location of river mouths, the direction and velocity of air currents, and the strength and direction of tidal currents. The interplay of all these and of various other factors will doubtless result in building on parts of the continental shelf deposits of great thickness and very considerable extent. Over other extensive areas nothing at all will be left by the ocean currents, and scour may result. The general result may be an irregularity of deposition as great as that which characterizes wind-blown deposits.

The comparatively small volume of clastics which an arid region like western Australia could furnish to its extended littoral zone would result in a minimum rate of deposition which would probably be much lower than that of any other continental coast line. This vast region which is essentially a desert coast line of about 3,500 miles has not a single river of any size. The so-called rivers are mostly insignificant streams many of which are nearly dry unless during the rainy season.[2]

[1] Pilsbury, "The Gulf Stream; Methods of the Investigations and Results of the Research," *Rept. U.S. Coast and Geol. Survey* (1890), Appendix 10, p. 570.

[2] Henry M. Cadell, "Some Geological Features of the Coast of Western Australia," *Edinburgh Geol. Soc. Trans.*, VIII (1899), 174.

If with the littoral zone of western Australia such an area as the Bay of Bengal is contrasted, the enormous difference in the volume of clastic sediments which comes to rest on different parts of the sea bottom is clearly seen. The upper part of the Bay of Bengal receives the drainage from the southern slopes of the Himalaya Mountains where in places the rainfall amounts to 472 inches or nearly 40 feet per annum.[1]

Rôle of vegetation in estuaries.—Closely related to the relative aridity of the sea coast in different parts of the world is the variable rate at which sedimentation on different coasts transforms shallow estuaries into marshes and eventually into dry land. When sedimentation has developed to the stage of shifting sand banks in an estuary, vegetation becomes the chief factor in fixing these and in extending land conditions. In an arid climate the virtual absence of this factor may cause the last stages of filling to proceed with extreme slowness while in a moist climate they will develop with relative rapidity. The rôle of vegetation as a factor in late stages of sedimentation is well illustrated in Professor Oliver's study of the plant life of a salt marsh in Brittany called the Bouche d'Erquy.

> Sand litters the beach, and in part is blown by the winds to form the barrier of sand dunes. Another part is brought into the estuary and is driven hither and thither by every tide. So restless are the shifting sands in the lower part of the estuary that plants cannot gain a footing, though seed be scattered far and wide. Higher up as we saw stability has been reached, and the ground is held by a turf of halophytes, and half way up the estuary where the bare and covered parts adjoin, the restless sands are tamed and bound. The transition from the fixed marsh to the mobile sand is a gradual one. The continuous carpet of the former gives place to scattered hummocks or tussocks of *Obione portulacoides* and the perennial *Salicornia radicans.* Beyond this the *Obione* dies out and the *Salicornia radicans* carries on its colonizing work alone. This it does by throwing out each year its seeds which germinate on the treacherous sand. . . . . In some places the pioneers are advancing at a rate of 10 feet a year, elsewhere less rapidly; whilst in spots where the sand is very mobile they seem perfectly stationary but the local conditions are always changing and the most unpromising surroundings may give place at any time to such as favour a rapid advance. A rough estimate based on the rate of progress noted during the last three years and on the assumption that this rate will

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[1] G. T. Bonney, *The Structure of the Earth*, p. 40.

not be checked would indicate that two hundred to two hundred and fifty years must elapse before the whole estuary is carpeted with halophytes.[1]

Periodic and cataclysmic variations.—Variations in sedimentation which correlate with a time factor may be referred to two classes: (1) periodic or seasonal, and (2) those without any definite period of recurrence which may be termed cataclysmic. To the first class belong the differences in the quantity of sediment which is deposited on a delta front during the spring flood period and the winter season. Such differences may be recorded in banding or lamination similar to those which Sayles[2] has interpreted as of seasonal origin in certain aqueoglacial deposits. To the cataclysmic order of variability belong the profound alterations in coast lines and in shifting of the sediments near them which result from phenomenal tides, great storms, and tidal waves. The Bay of Fundy has furnished a good example of tides of extraordinary height in the Saxby tide, which accompanied the heavy Saxby gale of October 5, 1869.[3] The destruction of the city of Galveston a few years ago, resulting from the piling up of sea water on a low shore by a great storm, illustrates well the profoundly destructive character of storms of maximum intensity which may recur only at intervals of one or more centuries. The folklore of many races affords evidences of such phenomenal disturbances in the normal relations of land and sea in the form of legends regarding a universal deluge.

The rise of the sea to an unusual height resulting from tempests of exceptional violence over low-lying lands which occurs at widely separated intervals along some coasts has frequently resulted in sudden and most comprehensive alterations of the physical geography. The piling up of the water of the North Sea on the north coast of Holland has repeatedly resulted in submergence and great disaster to extensive areas in Holland within the historical period. It is estimated that 2,336 square miles[4] have been swallowed by the sea in Holland since the thirteenth century. One of the most remarkable of these changes produced the Zuyder Zee. In the thirteenth century

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[1] F. W. Oliver, "An Experiment in Co-operative Fieldwork in Botany," *The Southeastern Naturalist* (England, 1907), p. 41.

[2] R. W. Sayles, "Seasonal Deposition in Aqueoglacial Sediments," *Mem. Mus. Comp. Zoöl.*, XLVII (1919), 1–63, pls. 1–16.

[3] Robert Chalmers, *Can. Geol. Surv. Ann. Rept.*, Vol. 7, n.s., 1894 (1896).

[4] E. Reclus, *The Earth and Its Inhabitants*, III, 462.

> the low lands along the Vlie, often threatened, at last sank in the waves. The German Ocean rolled in upon the inland lake of Flevo. The stormy Zuyder Zee began its existence by engulfing thousands of Frisian villages, with all their population and by spreading a chasm between kindred peoples.[1]

The political as well as the geographical continuity of the land was obliterated by this tremendous deluge. Another of these great inundations occurred in 1570.

> A continued and violent gale from the northwest had long been sweeping the Atlantic waters into the North Sea, and had now piled them upon the fragile coasts of the provinces. The dykes, tasked beyond their strength, burst in every direction. The cities of Flanders to a considerable distance inland were suddenly invaded by the waters of the ocean.[2]

ORGANIC AND BIOCHEMICAL DEPOSITS

Limestone of biochemical origin.—In the case of non-clastic sediments variability in the rate of accumulation in different areas is probably as pronounced as it is in clastic sediments. There is little available data concerning the rate at which limestone sediments accumulate. But it is probable that a seasonal factor may become recognizable. The formation of limestones of biochemical origin is confined to rather definite geographical areas. Although sea water generally contains about 2,000,000 tons of calcium to the cubic mile[3] it is being extracted and built into rock formations within the confines of the tropics and subtropics in far greater quantities than elsewhere. The development of coral reefs, the formation of calcareous deposits by denitrifying bacteria and the lithification of shore deposits are the principal elements in the inequality of the distribution of calcareous sediments. The limitation of the action of each of these agencies to wide belts on either side of the equator strongly tends to confine the formation of considerable deposits of limestone to the tropical and subtropical seas.

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[1] J. L. Motley, *The Rise of the Dutch Republic*, Historical Introduction VI, Vol. I, p. 35 (London, 1913).

[2] *Op. cit.*, Vol. II, Part III, chap. v, pp. 285–87.

[3] John Murray, *Nature*, XXXIX (1889), 426.

Much has been accomplished in recent years toward delimiting the factors responsible for the areal limitations on limestone formations. The more recent work which has been done on the biochemical factors chiefly concerned in the formation of limestone has been summarized by Vaughan.[1]

In the Florida-Bahama region occur vast areas of chalky mud. These give place to non-calcareous sediments farther north. Dr. Vaughan's work on the Florida coast has shown that the bottom deposits now forming inside the Florida Keys varies from quartz sand to nearly pure calcareous ooze. He writes:

> Silica is abundant in the form of sand in the northern portion of Biscayne Bay, it becomes rarer toward the southwest and is present in small quantities as far as Big Pine Key. Toward the southwest as the silicious material becomes rarer, calcium carbonate becomes progressively more abundant, occurring as a flocculent sediment or ooze over practically the entire region from the lower portion of Biscayne Bay to the Gulf end of Florida Bay.[2]

The important discovery by the late Dr. G. H. Drew[3] of the part played by marine bacteria in producing chemical conditions favorable to the precipitation of calcium carbonate gave the first clue to the mode of origin of these incipient limestones of the Florida Keys. The environment considered especially favorable for these denitrifying bacteria includes a tropical or subtropical climate with "drainage into the sea of a well-wooded country composed of calcareous rock and the soluble organic calcium salts would be precipitated as calcium carbonate by the action of the bacteria."[4]

Coral reefs.—The contribution of corals to limestone formation is made chiefly in the form of fringing reefs some of which, like the Great Barrier reef of Australia, are several hundred miles in length.

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[1] T. W. Vaughan, "Chemical and Organic Deposits of the Sea," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 933–44.

[2] T. W. Vaughan, "A Contribution to the Geological History of the Floridan Plateau," *Carnegie Inst. of Washington, Pub. 133* (1910), p. 119.

[3] G. H. Drew, *Year Book Carnegie Inst. No. 10* (1911), p. 125.

[4] *Ibid.*, p. 139.

They occur also in detached masses called *chapeirões* on the coast of Brazil which Hartt described as follows:

> Corals grow over the bottom in small patches in the open sea, and without spreading much often rise to a height of forty to fifty or more feet like towers, and sometimes attain a level of low water, forming what are called on the Brazilian coast *chapeirões*. At the top these are usually very irregular and sometimes spread out like mushrooms, or as the fishermen say like umbrellas. Some of these *chapeirões* are only a few feet in diameter.[1]

Lithification.—Lithification of unconsolidated materials is a potent factor in permanently fixing on the seashore and bottom deposits of shifting sands, gravel, and other materials. Lithification of loose sediments by the deposition of Ca_2Co_3 is subject in a general way to latitude control. On the Atlantic coasts it is a relatively unimportant factor north of Florida on the American side and is seldom reported north of France on the European coast. The action of this factor on the coasts where it is common and important is highly irregular and as yet imperfectly understood. On the northeast coast of Brazil it has produced the curious wall-like reefs bordering the shoreline which have been described in detail by Branner.[2] Similar structures occur in the Levant which have been described by Lartel,[3] Hull,[4] and others. Beaufort[5] shows that the ancient port of Pompeiopolis in Asia Minor has been filled with dune sands which have become solidified on the beach of the port. This case, Branner notes, shows that the lithification has occurred within historical times.

At the island of Ascension Darwin found on the sea beaches immense accumulations of small well-rounded particles of shells and corals. At the depth of a few feet these were found cemented together into stone. These calcareous masses had been under the observation of Lieutenant Evans for six years, who reported that there was an annual addition to them sometimes amounting to half an inch in thickness which began to deposit in October with the change in direction of the prevailing currents and which was later in the year in part re-dissolved by the waves.[1] This resolution of the calcium carbonate clearly indicates a seasonal factor in the formations of some limestones, deposition proceeding during only a portion of the year.

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[1] C. F. Hartt, *Geology and Physical Geography of Brazil* (Boston, 1870), pp. 174–200.

[2] J. C. Branner, "The Stone Reefs of Brazil," *Bull. Mus. Comp. Zoöl.*, XLIV (1904), 1–285, pls. 1–83C.

[3] L. Lartel, *Exploration gêologique de la Mer Morte de la Palestine* (Paris, 1887), p. 199.

[4] Edward Hull, *Mount Seir, Sinai, and Western Palestine* (London, 1889), p. 148.

[5] Francis Beaufort, *Karamania or a Brief Description of the South Coast of Asia Minor* (2d ed.; London, 1818), p. 249.

Variability of the Molluscan contribution.—The relative abundance of marine life on different parts of the sea bottom must be an important factor in the variation in rate of limestone accumulation in different areas. The general tendency of animal life to flourish best in shallow water is a well established fact. "Very many observations point to the conclusion that the density of life, both fishes and invertebrates, is greater on the sea bottom in close proximity to the land than in deeper waters farther out to sea. It is in such inshore waters that one finds the greatest wealth of animal life."[2] On the beach itself certain forms of marine life flourish in extraordinary abundance. At Fleshmick on the Isle of Man 2,940 individuals of *Balanaus balanoides* have been counted on one square foot of sea shore.[3]

In fresh-water lakes molluscan life is practically limited to depths less than 25 feet. Although a few fresh-water species have a bathymetric range much greater than this the contribution of such species to the calcareous element of lacustrine sediments is almost negligible. The bathymetric limitations of marine faunas are less abruptly drawn than those of fresh-water molluscan faunas, but they tend in the same direction, viz., toward a decrease in the amount of bottom life in deep water. It is evident from these facts that the molluscan contribution to limestone sediments would be largest along the inshore margin of the littoral zone. The seaward decrease seems to be somewhat irregular. This contribution is very considerable and varies greatly along different parts of the shore line. In one area a mussel bed may have a population of 16,000 molluscs to every square foot.[1] Another area may be practically barren of animal life. These barren areas occur in the tropics as well as elsewhere. Dr. Fred C. Baker[2] has called the writer's attention to a portion of the northeast coast of Brazil where molluscan life is extremely scarce.

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[1] Charles Darwin, *Geol. Observations* (1851), p. 49.

[2] James Johnson, *Conditions of Life in the Sea.* A Short Account of Quantitative Marine Biological Research (1908), p. 176.

[3] Catherine Maynie, "Marine Biology at Port Erin," *32d Ann. Rept.* (1918), p. 12.

The data which has been recorded in connection with oyster culture is instructive in connection with any consideration of the part which marine molluscs play in furnishing material for limestones. It is reported[3] that the oyster when introduced into a Louisiana area where it had been previously unknown yielded 1,500 to 2,000 bushels per acre in two years. In this particular case the shells of a single mollusc contributed an annual average thickness of about 4 inches of calcareous material over the whole of the bottom on which they lived. These figures will serve to illustrate the very different rates at which marine shells contribute to the materials for limestone formation. Along those parts of a coast where large prolific species like the oyster are dominant the calcareous element of the sediments must increase much more rapidly than where less prolific and smaller species make up the fauna.

An important factor in the accumulation of marine shells in any given area is the delicate adjustment to a particular kind of bottom environment which characterizes most marine molluscs. The way in which this adjustment would operate with the sand-loving cockle of the English coast has been aptly pointed out by Hunt.

> Were the supply of sand in Torbay to be cut off, another common feature in geology might meet with an illustration, viz., the sharply defined zone in which fossils frequently occur. Were such supply to be cut off (and from the isolated patches of red sandstones that skirt the bay we see how much less it already is than it has been in past time) the sand-loving cockles could not fail to be affected, and might even become extinct in this locality at a very rapid rate.[4]

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[1] James Johnson, *op. cit.*

[2] Letter, June 12, 1912.

[3] Hugh M. Smith, *National Geographic Magazine*, XXIV (1913), 267.

[4] A. R. Hunt, "Notes on Torbay," *Rep. and Trans. Devonshire Association for the Advancement of Science, Literature, and Art*, X (1878), 186–87.

Bone beds.—A considerable portion of the fossil remains of vertebrate animals are found in "bone beds."

The term "bone bed" is in itself evidence of the tendency of vertebrate-fossil remains to accumulate in certain restricted zones and areas. Bone beds occur in each of the geological systems from the Devonian up. Even the few vertebrate remains which are known from the Ordovician may almost be said to represent a bone bed because of their abundance in a single zone. The Middle Devonian bone bed which forms the top of the Columbus limestone in Central Ohio is a representative Paleozoic deposit of this type. It has a thickness of 6 or 8 inches and consists of an "assemblage of millions on millions of generally imperfect but mostly recognizable organs or fragments of the bony structure of the forms of fish life most characteristic of the Devonian age."[1] This bed according to Stauffer[2] can be traced across the northern half of the state.

In the Upper Devonian shales of northern Pennsylvania occur numerous bone beds composed of the fragments of Catskill fishes. These beds of fish fragments are apt to vary from a few inches to a few feet in thickness and generally lie in the midst of beds which are barren.

The veteran collector C. H. Sternberg, who has probably collected more vertebrate fossils than any other living man, appears to have found the great majority of his fossils in bone beds. He states that

> all through the Belly River series of rocks are bone beds. In some places I secured hundreds, yes thousands of bones and teeth of many species, as well as shields of sturgeons and the enameled scales of gar-pikes as perfect as if picked up along a recent lake shore. There were also bones and shells of a great variety of soft shelled turtles and others, with beautifully sculptured shells; they range in size from less than six inches across to over two feet. Crocodile bones and the dermal or skin plates of plated dinosaurs were common. We secured hundreds of the pavement teeth of the ray Cope called *Myledaphus*, also countless vertebrae of the reptile *Champsosaurus*.[3]

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[1] J. S. Newberry, *Monog. U.S. Geol. Surv.*, XVI (1889), 30.

[2] C. R. Stauffer, *Geol. Surv. of Ohio Bull. 10* (1909), p. 26.

[3] C. H. Sternberg, *Hunting Dinosaurs* (1917), p. 84.

C. M. Sternberg states that he knows of "no less than 7 bone beds in which only horned dinosaurs are represented."[1] Bone beds are frequently referred to in paleontological papers as "quarries." Concerning some of these quarries in Alberta Barnum Brown writes as follows:

> Frequently remains of many *Trachodonts* are found massed together in quarries, probably as a result of water action, in the Belly River and in the Edmonton strata, and there are two records of such occurrence in the Lance. In such quarries it is not exceptional to find *Trachodonts*, carnivorous dinosaurs, *Ceratopsia* and other remains commingled, although *Trachodonts* usually predominate.[2]

Various explanations have been offered for these aggregations of vertebrate remains, each of which is probably applicable to certain cases. Suffocation and burial by sand storms of the "frightened multitudes which had herded together in search of safety or courage" is a hypothesis offered by C. H. Sternberg.[3] Land vertebrates living in a wide alluvial plain might be periodically surrounded and herded together and drowned on the highest parts of an extensive area. In some instances prairie or forest fires may have been the compelling force which drove multitudes of land vertebrates into lakes and rivers. The fondness of most mammals for salt leads them, as is well known, to visit saline springs, and where these springs are in the midst of boggy ground may result in such aggregations of bones as those of the famous Bone Lick of Kentucky. Sir Charles Lyell[4] suggested still another way in which great numbers of large vertebrates may sometimes be drowned in lakes and rivers. He states that "It is well known that, during great droughts in the Pampas of South America, the horses, cattle, and deer throng to the rivers in such numbers that the foremost of the crowd are pushed into the stream by the pressure of others behind and are sometimes carried away by thousands and drowned."

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[1] Letter to the writer, January 7, 1919.

[2] *Bull. Amer. Mus. Nat. Hist.*, XXXVII (1917), Art. X, pp. 282–84.

[3] Sternberg, *Life of a Fossil Hunter* (1909), p. 132.

[4] Sir Charles Lyell, *Travels in North America in the Years 1841 and 1842*, pp. 141–42.

Charles Darwin described a very curious habit of the guanaco or llama of South America which if shared by many of the extinct vertebrates may help to explain some of the bone beds of the Cretaceous and other rocks.

> The guanacos appear to have favorite spots for lying down to die. On the banks of the St. Cruz in certain circumscribed spaces, which were generally bushy and all near the river, the ground was actually white with bones. On one such spot I counted between ten and twenty heads. I particularly examined the bones; they did not appear as some scattered ones which I had seen gnawed or broken as if dragged together by beasts of prey. The animals in most cases must have crawled, before dying, beneath and amongst the bushes. Mr. Bynoe informs me that during a former voyage he observed the same circumstance on the banks of the Rio Gallegos. I do not at all understand the reason for this but I may observe that the wounded guanacos at the St. Cruz invariably walked towards the river. At St. Jago in the Cape de Verd Island, I remember having seen in a ravine a retired corner covered with bones of the goat; we at the time exclaimed that it was the burial ground of all the goats in the island.[1]

The periodic migration habit which characterizes many species of vertebrate animals tends strongly toward a highly irregular and localized distribution of their fossil remains. The migrating instinct which is remarkably developed in the majority of the birds of the temperate zone, in many species of fishes and in some of the mammals results in the great bulk of the species concerned dying in either its summer or winter habitat or in some especially hazardous portion of its semiannual journey. This habit is typically developed in the caribou of northwest Canada. The summer range and breeding ground of this deer lies several hundred miles to the north of its winter habitat. The number of individuals which move south each autumn from the Arctic barrens to the forested lake region of north central Canada numbers hundreds of thousands if not millions of individuals.[2] The bulk of the herds follow certain well-defined routes and generally cross certain east to west trending lakes at certain points. If we consider the thousands of years that this movement has been going on and the frequent casualties which have probably occurred in crossing on the new autumn ice at points like Fond du Lac and Fort Rae on Great Slave Lake, we will see how at certain such points in the lakes and in the bogs which lay near the routes of migration the bodies of numberless caribou may have been entombed while other lakes and bogs remote from the north and south routes of migration might be entirely free from such remains.

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[1] Charles Darwin, *The Voyage of the Beagle*, p. 172.

[2] E. M. Kindle, "A Note on the Migration of the Barren Ground Caribou," *Ottawa Naturalist*, XXXI (1917), 107–9.

Some species of animals which do not possess the seasonal migration instinct are subject to waves of migration which recur at irregular intervals often separated by two or more decades. Such waves appear to be caused by an excessive increase in the numbers of a species within its normal habitat. The rapid-breeding Siberian lemming is subject to these migration waves. Dr. Brehm[1] vividly describes the way in which impending famine starts an exodus from an overpopulated tundra.

> Famine threatens, perhaps actually sets in. The anxious animals crowd together and begin their march, hundreds join with hundreds, thousands with other thousands, the troops become swarms, the swarms armies. They travel in a definite direction at first following old tracks, but soon striking out new ones; in unending files—defying all computation—they hasten onwards; over the cliffs they plunge into the water. Thousands fall victims to want and hunger; the army behind streams on over their corpses; hundreds of thousands are drowned in the water or are shattered at the foot of the cliffs; the remainder speed on; other hundreds and thousands fall victims to the voracity of Arctic and red foxes, wolves and gluttons, rough-legged buzzards and ravens, owls and skuas which have followed them; the survivors pay no heed.[2]

The famine crazed hordes of migrating individuals which may result when a species greatly outbreeds the food possibilities of its habitat have probably furnished important contributions to the fossil bone beds of previous epochs as they are doing to those of the present.

Phenomenal increase in the animalcule life of fresh and salt water sometimes results in the pollution of the water and destruction of all the life in it. The oldest recorded example of this kind is probably the biblical one of the Egyptian plagues when the water of the Nile was as it were "turned to blood and all the fish died."[3]

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[1] A. E. Brehm, *From the North Pole to the Equator*, p. 79.

[2] R. F. Scharff, *The History of the European Fauna* (1899), pp. 139–40.

[3] Exodus 7:20, 21.

The extraordinary abundance of flagellate animalcules is reported[1] to have caused red water for 200 miles along the coast of California and produced by their decomposition the death of shoals of fish and quantities of other marine animals. Phenomena of this kind must cause the sudden deposition on the sea bottom of unusual and extraordinary quantities of the remains of pelagic life of various kinds. If great numbers of fishes or other vertebrate animals were affected a bone bed might result.

Displacement of ocean currents.—Still another cause of discontinuity in the accumulation of marine fossils over extensive areas is to be found in the occasional shifting or displacement of ocean currents from parts of their usual routes by great storms. Professor Verrill encountered a striking example of this class of phenomena several years ago while dredging under the edge of the Gulf Stream, southeast of Long Island.

> One of the most peculiar facts connected with our dredging this season was the scarcity or total absence of many of the species especially of *Crustacea,* that were taken in the two previous seasons, in essentially the same localities and depths in vast numbers—several thousands at a time. . . . . An attempt to catch the "tile-fish" (*Lopholatilus*) by means of a long trawl-line on essentially the same ground where eighty were caught on one occasion last year, resulted in a total failure this year. It is probable, therefore, that the finding of vast numbers of dead tile-fishes floating at the surface in this region last winter, as was reported by many vessels, was connected with a wholesale destruction of the life at the bottom, along the shallower part of this belt (in 70 to 150 fathoms) where the southern forms of life and higher temperatures (48° to 50°) are found. This great destruction of the life was probably caused by a very severe storm that occurred in this region at that time, which by agitating the bottom-water forced outward the very cold water that even in summer occupies the great area of shallower sea in less than 60 fathoms along the coast, and thus caused a sudden lowering of the temperature along this narrow warm zone where the tile-fish and the crustacea referred to were formerly found.[2]

Barren areas.—Certain areas in many seas appear to remain permanently almost entirely barren of life though surrounded by areas crowded with marine life. One of the reasons for such barren areas in the case of sandy bottoms is doubtless the tendency of sands to move rapidly under current action and smother the marine life which attempts to live on them. Dr. G. A. Huntsman, who has been engaged in studying the conditions under which marine animals live in the Gulf of St. Lawrence has directed attention to another factor in producing lifeless zones. He states:

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[1] *The Library of Natural History,* III (1906), 768.

[2] A. E. Verrill, "Evidence of Great Destruction of Life Last Winter," *Amer. Jour. Sci.,* XXIV (1882), 366.

> By means of these traps we discovered that a barren zone existed off the Cape Breton shore, comprising the part of the sloping bottom between the depths of 10 and 20 fathoms. In this zone the temperature at the bottom underwent violent fluctuations, often in the course of a day or so, at one time being as high as 65° F., and at another as low as 39° F. This was caused by the winds, for when the wind was blowing on-shore it drove the surface water against the coast and heaped it up forcing the deeper colder water down; then when it changed and blew off-shore the warm surface water was driven away from the coast and the cold water welled up from below to take its place, and so flooded the zone. The effect of this on the slow moving bottom animals may be imagined. Few of them would be able to stand such changes, but the active fishes are able to move up and down the slope and avoid these changes.[1]

Seasonal variation.—Another factor in the variation in the rate of sedimentation in the sea is the seasonal factor. The annual seasonal changes in the sea result in marked differences in the amount of organic materials deposited on the sea bottom during different parts of the year. The registration of seasonal changes by banding in the volume of clastic sediments in aqueoglacial deposits has been exhaustively discussed by Sayles.[2] Comparable with the great contrasts in the volume of lacustrine sediments deposited during different parts of the annual cycle are the different amounts of organic materials which the plankton life of the sea showers on the bottom in winter and in summer. It is possible that we may yet be able to interpret some of the fine lamination in sea-laid deposits in the precise terms of years. "In early spring there is a great awakening in the oceans comparable with the growing of the grass and the budding of the trees on land." This awakening corresponds to the time when the alkalinity of the sea is at a maximum.

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[1] *Canadian Fisherman*, May, 1917.

[2] R. W. Sayles, *op. cit.*

Prof. Benj. Moore discovered that the sea around the Isle of Man was a great deal more alkaline in spring (say April) than it is in summer (say July); and then on examining monthly samples taken throughout the year he was able to show that the alkalinity which gets low in summer increases somewhat in autumn, then decreases rapidly during the winter, and after several months of a minimum begins to increase again in March, and rapidly rises to its maximum in April. That is the periodic change of alkalinity and it will be seen to correspond roughly with certain very important changes in the living microscopic contents of the sea and the connection between the two may be made out by inquiry into the nature and meaning of the changes in alkalinity. The alkalinity of the sea is due to the relative absence of carbon dioxide. . . . . We find that at Port Erin in March the water, not only on the shore, but also out in the open sea, is acid to phenolphthalein, while a month later it is distinctly alkaline to the same indicator and this change signifies an enormous conversion of carbon in the inorganic into carbon in the organic form, a turnover of such extent that it probably amounts to 20,000 or 30,000 tons of carbon per cubic mile of sea-water. . . . . Or we may imagine this same quantity of carbon as forming the bodies of all the organisms found in the sea all around the shores of the Isle of Man, in which case the 300,000 tons would be distributed through the zone of water extending to about one mile out from the shore and down to an average depth at that distance of, say, ten fathoms. Now all of these organisms have obtained their carbon from the carbon dioxide present in the sea-water in spring and it is absolutely certain that in the absence of this abundant supply of available carbon-food, the millions and millions or organisms in question could never have existed." . . . . "Practically all our food-fishes in the sea, except the herring, produce their eggs in winter or early spring. They are hatching out in vast quantities during the time that the alkalinity is rapidly increasing and the phytoplankton of diatoms is daily growing in amount."[1]

It is evident that the vast increase in the quantity of marine life during the spring and summer must be registered in sea-bottom deposition by a corresponding increase in the amount of diatom and other organic materials dropped on the sea bottom. We have therefore throughout the seas of the temperate and northern parts of the earth annually a summer period of maximum sedimentation following a winter period of minimum sedimentation.

CONCLUSIONS

The evidence appears to be distinctly against uniformity in sedimentation. Biologists in recent years have generally accepted the relatively new conception of succession as a process which results inevitably from the activities of each plant or animal community destroying by its own activities the possibility of indefinitely continued existence in the same place. The operation of this and other factors, some of which produce more sudden results, tend inevitably to vary the rate and shift the area of accumulation of the organic constituents of sediments. In a comparable manner sedimentation sets its own time limit on its operation in any given area. Alluviation terminates automatically when the deposits of a valley reach a thickness corresponding to the height of the maximum flood waters of the valley. Sedimentation ceases in a lake when the deposits approximate the lake surface. Although this familiar conception of the self termination of terrestrial sedimentation in fluvial and lacustrine waters has been generally recognized and applied to terrestrial sediments it has not been extended to marine conditions. But its application though less obvious is almost equally justified. In foreland structures the building of coarse deposits of sand, gravel, and shingle is limited vertically by the height to which wave action reaches. Horizontally the direction and strength of currents are the chief limiting factors. When these rather definite limits have been reached by a particular spit its supply of sediments goes elsewhere.

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[1] W. A. Herdman, "Some Periodic Changes in Nature," *32d Ann. Rept. Liverpool Marine Biology Committee* (1918), pp. 23, 24, and 27.

In areas remote from the shore line wave base and current action are determining factors in sedimentation. Wave base differs for different classes of materials as pointed out by Barrell.[1] It is deeper for fine than for coarse materials. Mud deposits can never build to the surface in the open sea because of the dissipating influence of the waves. Sand deposits fed by an abundant supply may, however, reach the surface. Whatever the upper limit of a particular formation may be, it will depend on the interplay of wave and current action, and when reached the further growth will be lateral or else diverted to a new area by a shifting of the flow of materials. Any adequate conception of marine sedimentation must include numerous great river-like currents some with intermittent activity, others periodic, while a few doubtless follow permanent routes in the sea bottom. Many of these probably move the finer sediments toward and over the border of the continental shelf as definitely as terrestrial streams move their sediments toward the sea.

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[1] Jos. Barrell, "Rhythms and the Movement of Geologic Time," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 778.

Geologists and paleontologists may learn much regarding the rôle of marine currents from the keen analysis of living faunas which such investigators as Peterson are making. This author who has discriminated and mapped several sharply contrasted bottom faunas in the Skagerrak and Kattegat finds that

> The *Modiola* epifauna occurs especially where there is a strong current close to the bottom, clearing away the finer particles so that stones and shells lie exposed, affording sites for attachment for the *Modiola*, which may here occur in such numbers as entirely to cover the bottom (see Pl. IX) for great tracts in the current channels.[1]

The inferences which we can at present make concerning some of the conditions controlling marine sedimentation are based on such detached bits of evidence as have been brought together in this paper. It is hoped, however, that it will soon be possible to base conclusion relating to such problems on intensive studies of numerous selected areas of sea bottom in which areal mapping of bottom deposits will be an important feature.

[1] C. G. Joh. Peterson, "The Sea Bottom and Its Production of Fish Food," *Rept. Danish Biol. Sta. to Board of Agriculture* (1918), p. 15.